Shipboard Electrical System Modeling for Early-Stage Design Space Exploration

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***Abstract*—In early-stage design exploration, it has been found that electrical dynamics do not significantly affect the dependability of an integrated engineering plant. Therefore, it has been found useful to neglect these electrical dynamics and focus on mechanical, thermal, and fluidic dynamics in assessing system performance. Previous methods of accomplishing this goal involve the use of linear programming to describe the behavior of the electrical system. Herein, two significant shortcomings of the existing linear programming methods are identified, and a method of representing the electrical system that addresses these shortcomings is proposed. The proposed method is demonstrated in several system studies.**

I. Introduction

The integrated engineering plant (IEP) of an electric warship can be viewed as a service provider that is responsible for providing services such as electric power and thermal management to the mission loads that it serves [1]–[3]. As such, its performance must be measured with respect to its ability to provide continuity of service to these loads across the variety of scenarios in which it must operate [2], [4]. The desired IEP design should be dependable [5].

The operability metric has previously been defined as a measure of the performance of an IEP during a specific scenario [2]. Dependability metrics have been derived from the operability metric as measures of the IEP performance over the range of scenarios in which the IEP must operate [2]. The assessment and optimization of dependability require a great number of operability evaluations [2], [4]. Furthermore, it has been found that the electrical dynamics of the IEP have little effect on the dependability of the IEP so long as the electrical system has been well designed (e.g., stable) [4], [6]–[8]. Therefore, the computational burden of operability evaluation can be reduced by neglecting the electrical dynamics of the IEP in the IEP system simulation [4], [6]. A previously proposed approach to this has involved the use of linear programming to model the action of the power system [6]. In this approach, the mechanical dynamics associated with prime movers are retained, but the electrical power flow is modeled statically. A linear objective function is maximized in which the weights associated with each load are equal to the weights of the loads in the operability calculation. This objective function is a heuristic approximation of an ideal power management system in which the solution to the optimal power management problem is approximated by the solution to a static problem at each moment in time. While this approximation is potentially optimistic and does not completely represent the time dependence associated with the power management problem (particularly in the presence of energy storage), it is a useful approximation for early-stage design because it can be evaluated at a stage in the design process when little information about the power management system is available.

Neglect of IEP electrical dynamics has proven very useful for early-stage design space exploration [4], [7]. Herein, two significant shortcomings associated with previous methods for modeling the IEP in this manner are described. These shortcomings pose significant difficulties for the use of this technique for larger scale systems. Herein, a linear programming approach that alleviates these problems is proposed and demonstrated in several system studies. The remainder of this paper is organized as follows. In Section II, two significant shortcomings of the previous linear programming approach described in [6] are described. Then, the proposed linear programming approach is set forth in Section III. Next, the proposed method is demonstrated in Section IV.

II. Previous Method

Two significant shortcomings associated with the previous linear programming approach [6] have been identified and are addressed herein. The first shortcoming is the potential to attempt to solve infeasible linear programs. Due to the finite power slew rates of the prime movers, it is possible that, in the presence of sudden load shedding (e.g., due to disruptive conditions), no solution may be found in which a generators output power will be greater than or equal to its minimum power output. In this case, the generator would overspeed and trip offline. In the previous linear programming approach, such a situation would result in an infeasible linear program, the solver would indicate this, and the offending generator would be deactivated. In the proposed model, the linear program is always feasible. When a generators output must be less than its minimum output, it does so via a heavily penalized slack variable. A zero-crossing function associated with this slack is constructed, and this zero crossing can be located by the simulation solver in order to deactivate the generator. This

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14. ABSTRACT
In early-stage design exploration, it has been found that electrical dynamics do not significantly affect the dependability of an integrated engineering plant. Therefore, it has been found useful to neglect these electrical dynamics and focus on mechanical, thermal, and fluidic dynamics in assessing system performance. Previous methods of accomplishing this goal involve the use of linear programming to describe the behavior of the electrical system. Herein, two significant shortcomings of the existing linear programming methods are identified, and a method of representing the electrical system that addresses these shortcomings is proposed. The proposed method is demonstrated in several system studies.

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avoids the difficulty associated with handling infeasible linear programs; the linear programs are feasible by construction.

The second shortcoming associated with the previous linear programming approach to this problem involves the consideration of load sharing. In normal operation, generators may share power in proportion to their ratings. Similarly, converters might share zonal load, and propulsion drives may share responsibility for the ships thrust. In the previous linear programming approach, consideration of load sharing is performed by considering a large number of sharing cases independently. Each sharing case represents a situation in which one or more devices are explicitly sharing load, setting specific equality constraints on the outputs of these devices. Each case is represented by a separate linear program, and at each time step, each linear program is solved. The solution to the case that has the highest objective function is considered the correct solution. The requirement of solving multiple linear programs is problematic because linear programming is the most time consuming task in such a simulation. Herein, the linear programming approach is improved to require only one linear program solution per time step. This linear program is slightly larger in terms of decision variables. Load sharing is promoted in the cost function of the linear program, and equivalent results to those found in previous approaches are found.

III. Linear Programming Approach

The linear-programming approach to electrical power system modeling involves approximating the behavior of the power system using a static linear program at each time step. Linear programs of the following structure are derived:

$$\begin{aligned} &\max_{\mathbf{x}} \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to } &\mathbf{A}\mathbf{x} \le \mathbf{b} \\ &\mathbf{A}_{eq}\mathbf{x} = \mathbf{b}_{eq} \\ &\mathbf{x} \ge \mathbf{0}. \end{aligned} \tag{1}$$

The elements of the vector $\mathbf{x}$ correspond with variables describing the operation of various elements in the power system. These elements and their constraints are described below.

A. Interconnect Model

Each interconnect represents a point at which two buses (a "from" bus and a "to" bus) may be disconnected. The manner of this disconnection (e.g., dc circuit breaker vs. deenergizing the bus and using low-current switches) is not considered at this level of modeling fidelity. It is simply assumes that the interconnects allow power to flow between buses within the power rating of the interconnect as long as each bus is intact. Each interconnect is represented by two variables P_{to} and P_{from}, and the total power flowing from the "from" bus to the "to" bus associated with the interconnect is $P_{to} - P_{from}$. The decomposition of the interconnect power into the difference of two nonnegative powers facilitates the linear-programming description of the system. Each power is limited such that

$$P_x \le \begin{cases} P_{max}, & \text{"from" and "to" buses undamaged} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where $x \in \{to, from\}$ and P_{max} is the maximum capacity of the interconnect.

B. Generator Model

Each generator is represented as the generator and a disconnect capable of isolating the generator from the bus to which it is connected (the "to" bus). The generator has instantaneous minimum and maximum power capabilities P_{min} and P_{max} that describe the ramp rate limits associated with the generator. These are discussed below. The output power of the generator is described as the difference of two variables P_{out} and $\hat{P}_{out}$, i.e., the total output power is $P_{out} - \hat{P}_{out}$. This is a deviation from the linear-programming approach described in [6]. Therein, only one variable is used to represent the generator output, but this creates in a situation in which an infeasible linear program can result. In particular, this occurs in the case where the total system load (or the load present in some island) is insufficient for the generator to avoid output less than its P_{min}. When this happens, the generator would overspeed and trip offline. This behavior is modeled herein as well, but in a manner that avoids infeasible linear programs. In particular,

$$P_{out} \le \begin{cases} P_{max}, & \begin{array}{l}\text{"to" bus undamaged} \\ \text{and generator operational}\end{array} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

and

$$P_{out} \ge \begin{cases} P_{min}, & \begin{array}{l}\text{"to" bus undamaged} \\ \text{and generator operational}\end{array} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

describe the upper and lower bounds on the nominal component of the generator output power P_{out}, and

$$\hat{P}_{out} \le \begin{cases} P_{min}, & \begin{array}{l}\text{"to" bus undamaged} \\ \text{and generator operational}\end{array} \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

allows the total generator output power to fall below P_{min}. This deviation below the minimum power limit is penalized in the objective function (i.e., the vector $\mathbf{c}$), but it allows the linear program to remain feasible. Deviations below the minimum power limit are detected using the zero-crossing-detection functionality of a given ODE solver, and when they are detected, the generator is marked as inoperative. This is actually simpler than the method of detecting this condition in the previous formulation [6]. In this formulation, the condition can only be detected by determining that no linear program for the system is feasible at a point in time. However, the linear-programming solver will generally not indicate which constraint is causing the infeasibility. Therefore, there is not a straightforward approach for determining which generator should trip offline.

The generator is modeled to have a slew rate pP_{slew} at which its power can increase or decrease. This model is based on the generator model described in [6]. Herein, a slew rate of 10%/s is utilized, but different slew rates would be appropriate for different types of generators. In particular, the instantaneous output power P of a generator should lie between P_{min} and P_{max}. These operating limits evolve according to

$$\frac{dP_{min}}{dt} = \text{bound}\left(\frac{P_{min,ss}(P) - P_{min}}{\tau}, -pP_{slew}, pP_{slew}\right) \tag{6}$$

$$\frac{dP_{max}}{dt} = \text{bound}\left(\frac{P_{max,ss}(P) - P_{min}}{\tau}, -pP_{slew}, pP_{slew}\right) \tag{7}$$

where

$$P_{min,ss}(P) = \max\{(1-\epsilon)(P - P_{max,nl}), 0\} \tag{8}$$

$$P_{max,ss}(P) = \min\{(1+\epsilon)P + P_{max,nl}, P_{rating}\} \tag{9}$$

and τ is a time constant (set to 1 s) associated with the slew-rate limitation, ϵ is a coefficient (0.05) that describes the range in which the power can change instantaneously, and $P_{max,nl}$ indicates the amount of power that is available instantaneously from no-load conditions (here assumed to be 10% of rated power).

C. Converter Model

A converter represents a generic power conversion device that moves power from one bus (the "from" bus) to another bus (the "to" bus). The converter is represented as capable of isolating faults on either bus from the other. If this assumption does not hold, the method of calculating the status of a given bus can be extended to consider dependence on the status of another bus. The converter is also represented as capable of unidirectional power flow, but bidirectional power flow can be represented by two converters in antiparallel. Each converter has two power variables P_{in} and P_{out}. The output power is limited as follows:

$$P_{out} \leq \begin{cases} P_{rating}, & \text{"from" and "to" buses undamaged} \\ & \text{and converter operational} \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

and the input power is related by the converter's efficiency:

$$P_{in} = P_{out}/\eta. \tag{11}$$

D. Load Model

A load represents a sink for power connected to a bus (the "from" bus). The load power P_{in} is limited by the maximum power of the load (possibly time varying):

$$P_{in} \leq \begin{cases} P_{max}, & \text{"from" bus undamaged} \\ & \text{and load operational} \\ 0, & \text{otherwise.} \end{cases} \tag{12}$$

As the purpose of the power system is to provide power to its loads, the objective function rewards power delivery to each load in proportion to the current weight of that load. These weights are derived from mission requirements and vary with time and mission.

E. Bus Model

For each bus, the total power flowing into the bus must sum to zero. Therefore, for each bus, an equality constraint can be constructed such that

$$\sum P_{in} = 0. \tag{13}$$

This equality constraint can be constructed by consideration of the interconnects that join a bus with neighboring buses. For an interconnect in which the bus in question is the "to" bus, the incoming power is $P_{to} - P_{from}$. For an interconnect in which the bus is the "from" bus, the incoming power is $P_{from} - P_{to}$. For any generator connected to the bus, the incoming power is $P_{out} - \hat{P}_{out}$. For any converter in which the bus in question is the "from" bus, the incoming power is $-P_{in}$, and for any converter in which the bus in question is the "to" bus, the incoming power is P_{out}. For any load connected to the bus, the incoming power is $-P_{in}$. One such equality constraint is constructed for each bus in the system.

F. Load Sharing

The consideration of load sharing is another manner in which the proposed method deviates from that proposed in [6]. In [6], it is noted that there are situations in which generators or converters should share their total load in proportion to their ratings. However, under abnormal operating conditions, a requirement that this happen can result in less total power being delivered to loads. Therefore, sharing scenarios are constructed in [6] that describe every possible combination of components that could be sharing load at a point in time. These scenarios each induce a unique set of additional equality constraints on the output powers of the components governed by them. A linear program is then formulated and solved for each of these scenarios, and the scenario in which the solution is optimal from the point of view of load satisfaction and load sharing is selected. This involves consideration of various sharing groups. The generators are assumed to form one sharing group with the presumption that under normal operation load would be shared by each generator. Sets of converters that are capable of providing power to the same bus are considered sharing groups as well. Unfortunately, the number of sharing scenarios grows rapidly with the number of devices that can share load and with the number of sharing groups in which these devices participate.

Herein, the same challenge is addressed from the standpoint of a single linear program. This program has additional decision variables, but only one linear program needs to be solved at each time step. Each device that can share power is assigned a positive and negative deviation from the ideal power sharing scenario, α and β, respectively. In each sharing group, the devices that are active are determined. For generators, this means that the generator is operational and that its "to" bus is intact. For converters, this means that the converter is

operation and that its ”from” and ”to” buses are intact. The total rating $P_{rating,total}$ of all operational devices in the group is determined. An equality constraint for each operational device is established such that

$$\frac{P_{total}}{P_{rating,total}} - \frac{P}{P_{rating}} + \alpha - \beta = 0 \tag{14}$$

where P_{total} is the total power produced by each member of the sharing group, P is the power produced by the given device, and P_{rating} is the rated power of the given device. The factors α and β are (lightly) penalized in the objective function (i.e., the vector $\mathbf{c}$). In this way, the linear program will seek to deliver maximal power to highly weighted loads, but it will seek solutions where load is shared in cases where this can be done without affecting overall load satisfaction.

G. Method Summary

The proposed method will result in a linear program with $2n_i + 2n_g + 2n_c + n_l + 2n_g + 2n_{sgm}$ decision variables where n_i is the number of interconnects, n_g is the number of generators, n_c is the number of converters, n_l is the number of loads, and n_{sgm} is the number of converters that participate in sharing groups (sharing group members). The resulting linear program will have $2n_i + 3n_g + n_c + n_l$ inequality constraints and $n_b + n_c + n_g + n_{sgm}$ equality constraints where n_b is the number of buses. Furthermore, the approach will involve a differential equation describing the generators' power limits with $2n_g$ state variables.

This can be compared with the method in [6] in which multiple linear programs must be solved. Each linear program will have $2n_i + n_g + 2n_c + n_l$ decision variables, which is fewer than the proposed method. Each will have $2n_i + 2n_g + n_c + n_l$ inequality constraints, which is also fewer than the proposed method, and each will have between $n_b + n_c$ and $n_b + n_c + (n_g - 1) + (n_{sgm} - n_{sg})$ equality constraints depending on which sharing scenario is being considered where n_{sg} is the number of sharing groups in which converters can participate. The number of equality constraints for each of these linear programs is also less than those required for the proposed method. However, despite each linear program being smaller in size, a great number of these linear programs must be solved at each time step. In particular, the total number of cases that must be considered is the product of the number of scenarios in which power can be shared in each sharing group. The same differential equation describing the generators' power limits with $2n_g$ state variables is used with this method.

IV. Demonstration of Proposed Method

The proposed method is demonstrated on the Electric Ship Research and Development Consortium notional medium-voltage dc system as described in [8], [9]. A simplified depiction of this system is shown in Fig. 1. Herein, the energy storage and pulsed load are not represented because it is not necessary to demonstrate the relative advantages of the proposed method. These devices can be incorporated in a straightforward manner (e.g., as given in [6]). Likewise, the large load shown in the center of Fig. 1, which represents a radar load, is represented as drawing constant power in steady state. This representation could easily be substituted with an alternative representation without additional difficulty.

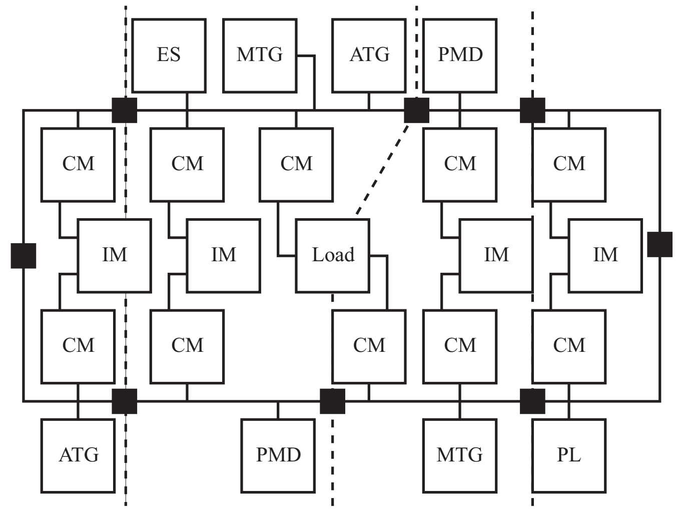

Fig. 1. Notional MVDC system. MTG signifies main generator, ATG signifies auxiliary generator, PMD signifies propulsion drive, CM signifies a dc-dc converter, IM signifies a converter to end-use form, ES signifies energy storage, and PL signifies pulsed load.

TABLE I
System Size

Parameter	Value
n_i	8
n_g	4
n_c	16
n_l	29
n_b	18
n_{sg}	6
n_{sgm}	12

In this system, each device resides in one of four electrical zones [10] with interconnects separating the zones. Also, interconnects exist in the forward and aft connections between the port and starboard sides of the system. The pairs of CMs that are aligned vertically are assumed to participate in load sharing. Also, the CMs providing power to the central load are assumed to participate in load sharing. Finally, the two propulsion drives are represented as converters providing power to a fictitious propulsion bus, with various amounts of required propulsion power being represented as loads on this bus. In this sense, the two propulsion drives also participate in load sharing. This system has the sizes shown in Table I.

This system requires a linear program with 117 decision variables, 50 equality constraints, and 73 inequality constraints. The previous linear programming approach discussed in [6] requires 81 decision variables, between 34 and 43 equality constraints, and 69 inequality constraints, but 960 linear programs must be solved per time step. In [6], a

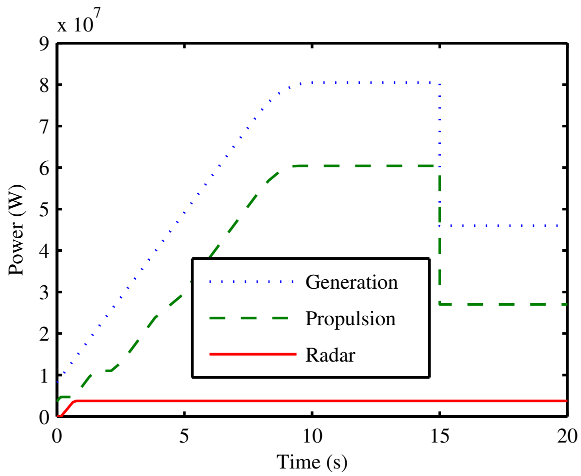

Fig. 2. Simulation results using the previous linear programming method

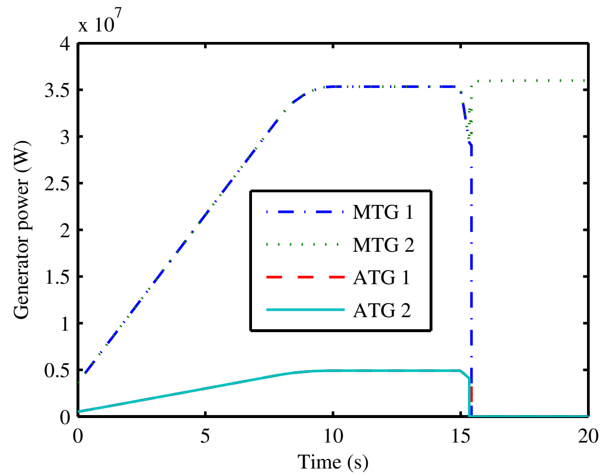

Fig. 4. Simulation results of 50% load shed in 1 s

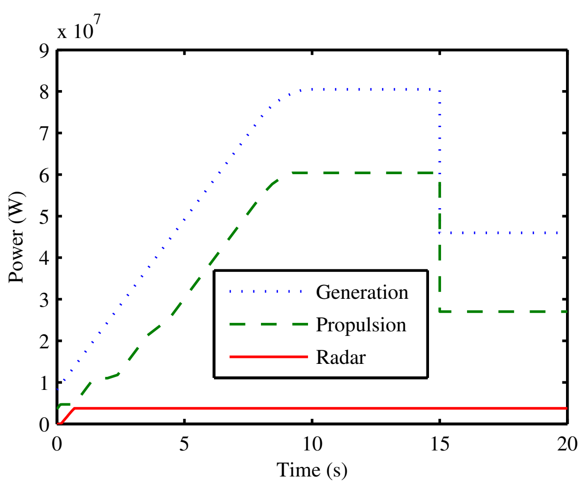

Fig. 3. Simulation results using the proposed linear programming method

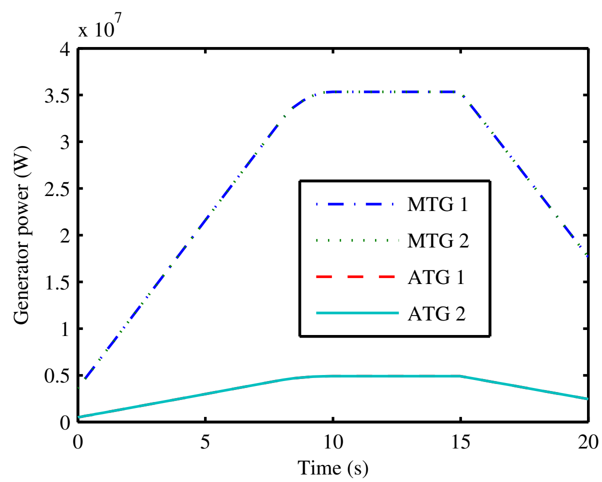

Fig. 5. Simulation results of 50% load shed in 5 s

simulation speed of 15 times faster than real time is reported for a smaller problem. To compare the two approaches, a case in which the system is brought to steady state and at 15 s a generator trips offline is studied. For this study, the loads are weighted in accordance with the weights provided in [8]. MATLAB's ode23tb solver [11] is used to integrate the differential equations and the lp_solve package [12] is used to solve the linear programs (this package was found to solve these linear programs in significantly less time than MATLAB's linear programming solver). The results of simulating the previous method are shown in Fig. 2. The results of simulating the proposed method are shown in Fig. 3. It can be seen that the two methods predict essentially identical system behavior. However, the previous method required 603 s to perform this 20-s study on an Intel Core i7 2.8-GHz processor with 4 GB of memory. On the same computer, the proposed method required only 1.01 s. The excessive computational cost associated with the previous method effectively precludes its use for early-stage design exploration for larger systems.

In another case that demonstrates the ability of the proposed method to detect generator overspeed conditions, the total system load is ramped from 100% to 50% over 1 s beginning at 15 s. The output power of each generator is shown in Fig. 4. This study required 1.30 s to simulate. It can be seen that this sudden load shedding causes both auxiliary generators and one of the main generators to trip offline. This behavior may be slightly unexpected as the auxiliary generators would probably have higher power ramp rate capabilities, but herein, the generators all have common ramp rate limitations. A more gradual load shedding scenario is shown in Fig. 5. In this case, the total system load is shed over 5 s, and this study required 0.99 s to simulate. In this simulation, no generators tripped offline because the load shedding could be handled within the ramp rate limits of the generators.

A final case that is considered is that of a bus fault occuring at the bus where the port main and auxiliary generators are connected. This simulation study lasts 1800 s. At 900 s, the fault occurs, and at 960 s, the system establishes new load

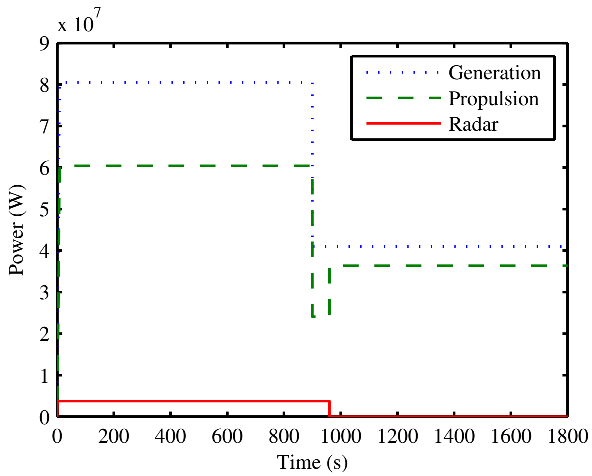

Fig. 6. Simulation results of bus fault followed by change in load weighting

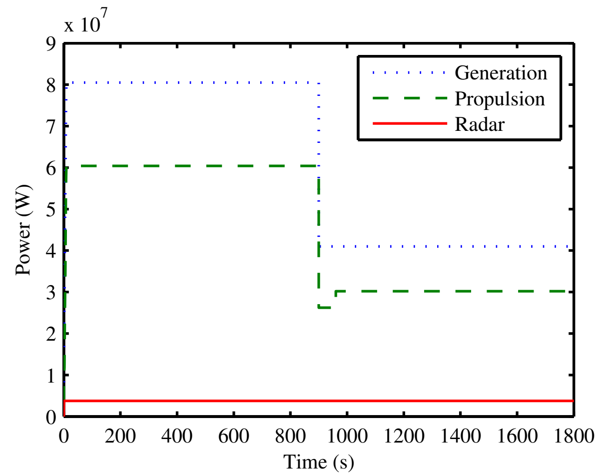

Fig. 7. Simulation results of bus fault followed by change in load weighting with interconnects deactivated

weightings in order to meet mission objectives. In particular, the weight of the propulsion load is promoted to exceed the weight of the radar load. The results of this study are shown in Fig. 6. It can be seen that the total generator power is reduced because the two generators trip offline. Also, the propulsion power is reduced, but the radar power maintains its value due to the weighting of the loads. When the load weights are updated at 960 s to emphasize propulsion, power shifts from the radar and other loads to propulsion.

A similar example is shown in Fig. 7. In this simulation, the interconnects between the port and starboard are deactivated. It can be seen that the generation and propulsion powers are reduced. However, when the system is reconfigured, power is not shifted from the radar load to propulsion. Instead, the propulsion load increases only slightly due to power being shifted from other loads. At this level, the total propulsion power is equal to the rated power of one of the propulsion drives. The other propulsion drive is inoperable because power cannot be delivered to it with the buses split in this manner. A comparison of the resulting ship speed is shown in Fig. 8. It can be seen that the case with the interconnects deactivated actually provides more speed during the 60 s following the fault. However, during this time, the load weightings are such that power would be better spent elsewhere in the system. Following the change in load weighting, the system with the interconnects active provides more speed.

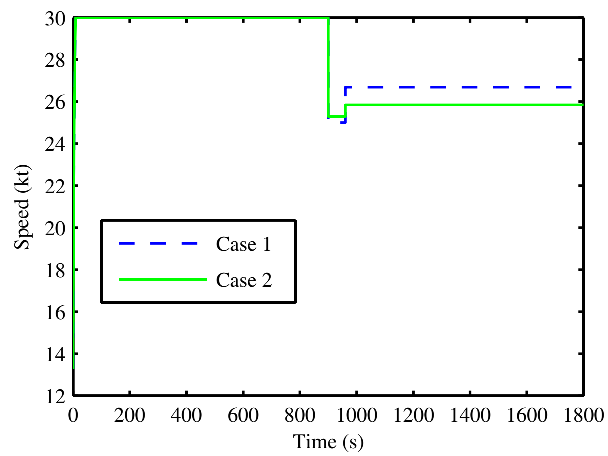

Fig. 8. Simulation results of ship speed following bus fault and change in load weighting. Case 1 represents interconnect active. Case 2 represents interconnects deactivated.

V. Conclusion

A previously proposed approach to model the power system has involved the use of linear programming. Two significant shortcomings associated with the previous linear programming approach have been identified. The first shortcoming is the potential to attempt to solve infeasible linear programs. The second shortcoming associated with the previous linear programming approach to this problem involves the consideration of load sharing. An improved method of modeling the shipboard electrical system for early-stage design space exploration is proposed herein. The proposed method addresses both of these shortcomings and has been demonstrated on a notional medium voltage dc system, allowing the method to be used in early-stage design space exploration studies.

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